Nucleon tomography: Experimental data fits

Nonperturbative aspects of field theory | H. Moutarde

Apr. 28th, 2017
Motivation.
QCD large distance dynamics from the hadron structure viewpoint.

Lattice QCD clearly shows that the mass of hadrons is generated by the interaction, not by the quark masses.


Can we map the location of mass inside a hadron?
Imaging the origin of mass.
Identification of underlying mechanisms from parton distributions.

How can we recover the well-known characteristics of the nucleon from the properties of its colored building blocks?
Imaging the origin of mass.
Identification of underlying mechanisms from parton distributions.

How can we recover the well-known characteristics of the nucleon from the properties of its **colored building blocks**?

**Mass?**
Imaging the origin of mass.
Identification of underlying mechanisms from parton distributions.

How can we recover the well-known characteristics of the nucleon from the properties of its colored building blocks?

Mass?
Spin?
Imaging the origin of mass.
Identification of underlying mechanisms from parton distributions.

Motivation
Mass without mass

Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions

How can we recover the well-known characteristics of the nucleon from the properties of its colored building blocks?

Mass?
Spin?
Charge?
Imaging the origin of mass.
Identification of underlying mechanisms from parton distributions.

How can we recover the well-known characteristics of the nucleon from the properties of its colored building blocks?

Mass?
Spin?
Charge?
...

Nonperturbative field theory 2017

H. Moutarde
Imaging the origin of mass.
Identification of underlying mechanisms from parton distributions.

How can we recover the well-known characteristics of the nucleon from the properties of its colored building blocks?

Mass?
Spin?
Charge?
...

What are the relevant effective degrees of freedom and effective interaction at large distance?
Imaging the origin of mass.
Identification of underlying mechanisms from parton distributions.

Structuring questions for the hadron physics community

- **QCD mechanisms** behind the origin of mass in the visible universe?
- **Cartography** of interactions giving its mass to the nucleon?
- **Pressure** and **density** profiles of the nucleon as a continuous medium?
- **Localization** of quarks and gluons inside the nucleon?
Motivation.
Study nucleon structure to shed new light on nonperturbative QCD.

Perturbative QCD

Asymptotic freedom

Nonperturbative QCD

Perturbative AND nonperturbative QCD at work

- Define **universal** objects describing 3D nucleon structure: **Generalized Parton Distributions (GPD)**.

- Relate GPDs to measurements using **factorization**: **Virtual Compton Scattering (DVCS, TCS)**, **Deeply Virtual Meson production (DVMP)**.

- Get **experimental knowledge** of nucleon structure.
Anatomy of hadrons.
GPDs, 3D hadron imaging, and beyond (1/4).

- Correlation of the **longitudinal momentum** and the **transverse position** of a parton in a hadron.
- DVCS recognized as the cleanest channel to access GPDs.

Deeply Virtual Compton Scattering (DVCS)

\[
\gamma^* + p \rightarrow e^- + \gamma + p
\]

Transverse center of momentum \( R_\perp \)
\[ R_\perp = \sum_i x_i r_{\perp i} \]
Anatomy of hadrons.
GPDs, 3D hadron imaging, and beyond (1/4).

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### Deeply Virtual Compton Scattering (DVCS)

**DVCS**
\[ e^- + p ightarrow e^- + p + \gamma \]
\[ \gamma^* + p \rightarrow e^- + p + \gamma \]

**Transverse center of momentum**
\[ R_\perp = \sum_i x_i r_\perp i \]

**Impact parameter**
\[ b_\perp \]

**Factorization**
\[ \mu_F \]

**Content of GPDs**
\[ F_i(x; Q^2; t) \text{ for each parton type } i = g; u; d; \ldots \text{ for leading and sub-leading twists.} \]
Anatomy of hadrons.
GPDs, 3D hadron imaging, and beyond (1/4).

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Deeply Virtual Compton Scattering (DVCS)

\[ \gamma^*, Q^2 \rightarrow e^- \gamma \rightarrow e^- \]

Transverse center of momentum \( R_\perp \)
\[ R_\perp = \sum_i x_i r_{\perp i} \]

Impact parameter \( b_\perp \)

Longitudinal momentum \( xP^+ \)
Anatomy of hadrons.
GPDs, 3D hadron imaging, and beyond (1/4).

- Correlation of the **longitudinal momentum** and the **transverse position** of a parton in a hadron.
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Deeply Virtual Compton Scattering (DVCS)

- 24 GPDs $F^i(x, \xi, t, \mu_F)$ for each parton type $i = g, u, d, \ldots$ for leading and sub-leading twists.
**Probabilistic interpretation** of Fourier transform of GPD($x, \xi = 0, t$) in transverse plane.

\[
\rho(x, b_\perp, \lambda, \lambda_N) = \frac{1}{2} \left[ H(x, 0, b_\perp^2) + \frac{b_\perp^j \epsilon_{ji} S_i}{M} \frac{\partial E}{\partial b_\perp^2}(x, 0, b_\perp^2) \right. \\
\left. + \lambda \lambda_N \tilde{H}(x, 0, b_\perp^2) \right]
\]

**Notations**: quark helicity $\lambda$, nucleon longitudinal polarization $\lambda_N$ and nucleon transverse spin $S_\perp$.


**Can we obtain this picture from exclusive measurements?**

*Weiss, AIP Conf. Proc. 1149, 150 (2009)*
Anatomy of hadrons.
GPDs, 3D hadron imaging, and beyond (3/4).

Most general structure of matrix element of energy momentum tensor between nucleon states:

\[ \langle N, P + \frac{\Delta}{2} | T^{\mu\nu} | N, P - \frac{\Delta}{2} \rangle = \bar{u} \left( P + \frac{\Delta}{2} \right) \left[ A(t) \gamma^{(\mu} P^{\nu)} + B(t) P^{(\mu} i \sigma^{\nu)}_{\lambda} \frac{\Delta_\lambda}{2M} + \frac{C(t)}{M} (\Delta^\mu \Delta^\nu - \Delta^2 \eta^{\mu\nu}) \right] u \left( P - \frac{\Delta}{2} \right) \]

with \( t = \Delta^2 \).

Key observation: link between GPDs and gravitational form factors

\[ \int dx x H^q(x, \xi, t) = A^q(t) + 4 \xi^2 C^q(t) \]
\[ \int dx x E^q(x, \xi, t) = B^q(t) - 4 \xi^2 C^q(t) \]

Anatomy of hadrons.
GPDs, 3D hadron imaging, and beyond (4/4).

- **Spin sum rule:**
\[
\int \text{d}x x (H^q(x, \xi, 0) + E^q(x, \xi, 0)) = A^q(0) + B^q(0) = 2J^q
\]


- **Shear and pressure** of a hadron considered as a continuous medium:
\[
\langle N | T^{ij}(\vec{r}) | N \rangle N = s(r) \left( \frac{r^i r^j}{r^2} - \frac{1}{3} \delta^{ij} \right) + p(r) \delta^{ij}
\]

Polyakov and Shuvaev, hep-ph/0207153
Towards hadron tomography.
How can we make the best from experimental data?

1. **Scaling regime**: looking for Bjorken scaling.

2. **Extractions**: strategies to get GPDs or CFFs from data.

3. **PARTONS framework**: tools for GPD phenomenology and theory.

How can we make this picture? What do we learn from it?
Searching the scaling regime
Exclusive processes of current interest (1/2).
Factorization and universality.

DVCS

$e^-$

$\gamma^*$

$Q^2$

$e^-$

$x + \xi$

$x - \xi$

$p$

$p$

$t$

Q2

$\gamma^*$

$by$

$bx$

Generalized Parton Distributions

$e + e^{-}$

$Q^2$

$\gamma^*$

$by$

$nucleon$

Nucleon tomography

Motivation

Mass without mass
Nucleon structure
Content of GPDs

Scaling regime

Experimental access

DVCS kinematics
Universality tests

Extractions

Dispersion relations
Extraction methods

PARTONS framework

Design
Architecture
Fits results

Conclusions
Exclusive processes of current interest (1/2).
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Motivation
- Mass without mass
- Nucleon structure
- Content of GPDs

Scaling regime
- Experimental access
- DVCS kinematics
- Universality tests

Extractions
- Dispersion relations
- Extraction methods

PARTONS framework
- Design
- Architecture
- Fits results

Conclusions

Nonperturbative Perturbative

DVCS

Factorization

$e^-$ $\gamma^*$ $Q^2$

$x + \xi$

$p$

$x - \xi$

$p$

$e^-$

Generalized Parton Distributions

$\gamma^*$

$Q^2$

$nucleon$

$b_x$

$b_y$
Exclusive processes of current interest (1/2).
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Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions

Exclusive processes of current interest (1/2).
Factorization and universality.

Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions

Exclusive processes of current interest (1/2).
Factorization and universality.

Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions

Exclusive processes of current interest (1/2).
Factorization and universality.

Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions

Exclusive processes of current interest (1/2).
Factorization and universality.

Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions

Exclusive processes of current interest (1/2).
Factorization and universality.

Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions

Exclusive processes of current interest (1/2).
Factorization and universality.

Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions

Exclusive processes of current interest (1/2).
Factorization and universality.

Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions

Exclusive processes of current interest (1/2).
Factorization and universality.

Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions

Exclusive processes of current interest (1/2).
Factorization and universality.

Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions

Exclusive processes of current interest (1/2).
Factorization and universality.

Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions

Exclusive processes of current interest (1/2).
Factorization and universality.

Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions

Exclusive processes of current interest (1/2).
Factorization and universality.

Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions

Exclusive processes of current interest (1/2).
Factorization and universality.

Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions
Exclusive processes of current interest (1/2).

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**Motivation**
- Mass without mass
- Nucleon structure
- Content of GPDs

**Scaling regime**
- Experimental access
- DVCS kinematics
- Universality tests

**Extractions**
- Dispersion relations
- Extraction methods

**PARTONS framework**
- Design
- Architecture
- Fits results

**Conclusions**

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**DVCS**

\[ e^- \rightarrow \gamma^* \rightarrow e^- \]

Factorization

\[ x + \xi \rightarrow x - \xi \]

**DVMP**

\[ e^- \rightarrow \gamma^* \rightarrow \pi, \rho, \ldots \]

Factorization

\[ x + \xi \rightarrow x - \xi \]

**TCS**

\[ e^+ \rightarrow e^- \]

Factorization

**Generalized Parton Distributions**

---
Exclusive processes of current interest (1/2).
Factorization and universality.

**Motivation**
- Mass without mass
- Nucleon structure
- Content of GPDs

**Scaling regime**
- Experimental access
  - DVCS kinematics
  - Universality tests

**Extractions**
- Dispersion relations
- Extraction methods

**PARTONS framework**
- Design
- Architecture
- Fits results

**Conclusions**

Exclusive processes of current interest (2/2).

- **DVCS**
  - Perturbative
  - Nonperturbative

- **DVMP**
  - Perturbative
  - Nonperturbative

- **TCS**
  - Perturbative
  - Nonperturbative

Nonperturbative field theory 2017 | 11 / 41
Exclusive processes of current interest (1/2).
Factorization and universality.

DVCS

\[ e^- \rightarrow \gamma^* \rightarrow e^- \]

Factorization

DVMP

\[ e^- \rightarrow \gamma^* \rightarrow \pi, \rho, \ldots \]

Factorization

Generalized Parton Distributions

TCS

\[ e^+ \rightarrow \gamma \rightarrow e^- \]

Factorization

H. Moutarde | Nonperturbative field theory 2017 | 11 / 41
Bjorken regime: large $Q^2$ and fixed $xB \simeq 2\xi/(1 + \xi)$

- Partonic interpretation relies on **factorization theorems**.
- All-order proofs for DVCS, TCS and some DVMP.
- GPDs depend on a (arbitrary) factorization scale $\mu_F$.
- **Consistency** requires the study of **different channels**.

- GPDs enter DVCS through **Compton Form Factors**:

$$\mathcal{F}(\xi, t, Q^2) = \int_{-1}^{1} dx \, C \left( x, \xi, \alpha_S(\mu_F), \frac{Q}{\mu_F} \right) F(x, \xi, t, \mu_F)$$

for a given GPD $F$.

- CFF $\mathcal{F}$ is a **complex function**.
Need for global fits of world data. Different facilities will probe different kinematic domains.

Experimental data collected at 3 facilities:
- DESY
- CERN
- Jefferson National Laboratory
Need for global fits of world data. Different facilities will probe different kinematic domains.

Valence quarks

Experimental data collected at 3 facilities:
- DESY
- CERN
- Thomas Jefferson National Laboratory
Need for global fits of world data.
Different facilities will probe different kinematic domains.

Valence quarks

Experimental data collected at 3 facilities

Thomas Jefferson National Laboratory

Desy

CERN

Sea quarks

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access

DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions
Need for global fits of world data. Different facilities will probe different kinematic domains.

Valence quarks

Experimental data collected at 3 facilities, soon 4: EIC!

Thomas Jefferson National Laboratory

NSAC, Long Range Plan 2015: "We recommend [...] EIC as the highest priority for new facility construction"
Need for global fits of world data. Only a small subset of the $(\xi, t, Q^2)$ space is directly accessed.

![Kinematic reach of existing or near-future DVCS measurements](image_url)

- HERA
- HERMES
- JLab6

**Existing measurements**

- **Motivation**
- Mass without mass
- Nucleon structure
- Content of GPDs

- **Scaling regime**
- Experimental access

- **DVCS kinematics**
- Universality tests

- **Extractions**
- Dispersion relations
- Extraction methods

- **PARTONS framework**
- Design
- Architecture
- Fits results

- **Conclusions**
Need for global fits of world data. Only a small subset of the $(\xi, t, Q^2)$ space is directly accessed.
Kinematic reach of existing or near-future DVCS measurements

Need for global fits of world data.

Only a small subset of the \((\xi, t, Q^2)\) space is directly accessed.
Need for global fits of world data. Only a small subset of the \((\xi, t, Q^2)\) space is directly accessed.

Kinematic reach of existing or near-future DVCS measurements

Need an EIC to determine gluon GPDs

\(\xi \gtrsim 10^{-4}\)
Need for global fits of world data. Only a small subset of the $(\xi, t, Q^2)$ space is directly accessed.

Kinematic reach of existing or near-future DVCS measurements

Dominant and sub-dominant contributions to the DVCS amplitude in the large $Q^2$ limit?
Typical DVCS kinematics.
Probing gluons, sea and valence quarks through DVCS.

- Study the harmonic structure of $ep \rightarrow ep\gamma$ amplitude.

Diehl et al.,

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Kinematics</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$x_B$</td>
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<tr>
<td>HERA</td>
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<td>COMPASS</td>
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<td>HERMES</td>
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<tr>
<td>CLAS</td>
<td>0.19</td>
</tr>
<tr>
<td>HALL A</td>
<td>0.36</td>
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</tbody>
</table>
Goloskokov-Kroll (GK) model on DVCS.

No parameter of the GK model was tuned to analyse DVCS.

Differential cross section, HERA

Goloskokov-Kroll (GK) model on DVCS.
No parameter of the GK model was tuned to analyse DVCS.

Beam Charge Asymmetry, HERMES

\[ A_C^{\cos 0\phi} \]

\[ A_C^{\cos \phi} \]

Goloskokov-Kroll (GK) model on DVCS. 
No parameter of the GK model was tuned to analyse DVCS.

Beam Spin Asymmetry, CLAS

\[ A_{LU}^- (\phi) \]

\[ \langle x_B \rangle = 0.13 \quad \langle Q^2 \rangle = 1.17 \quad \text{GeV}^2 \]
\[ \langle x_B \rangle = 0.18 \quad \langle Q^2 \rangle = 1.37 \quad \text{GeV}^2 \]
\[ \langle x_B \rangle = 0.25 \quad \langle Q^2 \rangle = 1.69 \quad \text{GeV}^2 \]
\[ \langle x_B \rangle = 0.34 \quad \langle Q^2 \rangle = 1.99 \quad \text{GeV}^2 \]

Kinematic contributions. Evidence for contributions beyond twist or leading order.

$t/Q^2$ and $M^2/Q^2$ are not small!

Defurne et al., arXiv:1703.09442 [hep-ex]
Extracting GPDs or CFFs from experimental data
Dispersion relations and the line $x = \xi$.
Existence of a relation between $\text{Re} \mathcal{H}(\xi)$ and $H(x, \xi = x)$.

- Write dispersion relation at fixed $t$ and $Q^2$:

$$\text{Re} \mathcal{H}(\xi, t) = \Delta(t) + \frac{2}{\pi} \mathcal{P} \int_0^1 \frac{dx}{x} \frac{\text{Im} \mathcal{H}(x, t)}{\left(\frac{\xi^2}{x^2} - 1\right)}$$

- Use LO relation $\text{Im} \mathcal{H}(x, t) = \pi \left(H(x, x, t) - H(-x, x, t)\right)$.

- Up to the D-term form factor $\Delta(t)$, all the information accessible at LO and fixed $Q^2$ is contained on the line $x = \xi$.

Teryaev, hep-ph/0510031
Dispersion relations and actual data.
Too few kinematic bins to provide model-independent constraints?
Dispersion relations and actual data.
Too few kinematic bins to provide model-independent constraints?

GK model vs CLAS $A_{LU}$

3 to 4 $(x_B, t, Q^2)$ bins with $|t|/Q^2 \simeq 0.12$
Dispersion relations and actual data.
Too few kinematic bins to provide model-independent constraints?

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions

3 to 4 \((x_B, t, Q^2)\) bins with \(|t|/Q^2 \approx 0.12\)

Cuts on \(|t|/Q^2\)?
Unphysical region?
Overview of current extraction methods.
Problems: Model dependence? Uncertainties?

Local fits
Take each kinematic bin independently of the others.
Extraction of $ReH$, $ImH$, ... as independent parameters.

Global fit
Take all kinematic bins at the same time. Use a parametrization of GPDs or CFFs.

Hybrid: Local / global fit
- **Option 1** Local fits and then smoothness assumption.
- **Option 2** Local fits and then 1-parameter fit.

Neural networks
Exploratory stage for GPDs.
Overview of current extraction methods.
Problems: Model dependence? Uncertainties?

Local fits

Take each kinematic bin independently of the others.
Extraction of $ReH$, $ImH$, ... as independent parameters.


- **Almost model-independent**: relies on twist-2 dominance assumption and assume bounds for the fitting domain.
- Interpretation of **uncertainties** on extracted quantities? Contributions from measurements uncertainties, correlations between CFFs and fitting domain boundaries.
- Interpretation of **extracted quantities**? e.g. mixing of quark and gluon GPDs due to NLO effects.
- **Oscillations** between different $(x_B, t, Q^2)$ bins may happen.
- **Extrapolation** problem left open.
Overview of current extraction methods.
Problems: Model dependence? Uncertainties?

Local fits: What can be achieved in principle?

- Structure of BSA at twist 2:

\[
BSA(\phi) = \frac{a \sin \phi + b \sin 2\phi}{1 + c \cos \phi + d \cos 2\phi + e \cos 3\phi}
\]

where \( a = \mathcal{O}(Q^{-1}) \), \( b = \mathcal{O}(Q^{-4}) \), \( c = \mathcal{O}(Q^{-1}) \), \( d = \mathcal{O}(Q^{-2}) \), \( e = \mathcal{O}(Q^{-5}) \).
Overview of current extraction methods.
Problems: Model dependence? Uncertainties?

Local fits: What can be achieved in principle?

- **Structure of BSA at twist 2:**
  \[
  \text{BSA}(\phi) = \frac{a \sin \phi + b \sin 2\phi}{1 + c \cos \phi + d \cos 2\phi + e \cos 3\phi}
  \]

- **Underconstrained** problem (8 fit parameters: real and imaginary parts of 4 CFFs $\mathcal{H}$, $\mathcal{E}$, $\tilde{\mathcal{H}}$ and $\tilde{\mathcal{E}}$).
Overview of current extraction methods.
Problems: Model dependence? Uncertainties?

Local fits: What can be achieved in principle?

- Structure of BSA at twist 2:
  \[ \text{BSA}(\phi) = \frac{a \sin \phi + b \sin 2\phi}{1 + c \cos \phi + d \cos 2\phi + e \cos 3\phi} \]

- Underconstrained problem.

- Need other asymmetries on same kinematic bin to allow extraction of all CFFs (or add \( \sim 5-10\% \) systematic uncertainty).
Local fits: What can be achieved in principle?

- Structure of BSA at twist 2:

\[ \text{BSA}(\phi) = \frac{a \sin \phi + b \sin 2\phi}{1 + c \cos \phi + d \cos 2\phi + e \cos 3\phi} \]

- Underconstrained problem.

- Need other asymmetries on same kinematic bin to allow extraction of all CFFs.

- Add physical input? Dispersion relations, etc.

Guidal et al., Rept. Prog. Phys. 76, 066202 (2013)

Overview of current extraction methods.

Problems: Model dependence? Uncertainties?

Global fit

Take all kinematic bins at the same time. Use a parametrization of GPDs or CFFs.


- Model-dependent approach.
- Allows the \textbf{implementation of theoretical constraints} on GPDs or CFFs.
- Guideline for \textbf{extrapolation} outside the physical domain.
- Compromise between number of parameters and number of described GPDs (flavor dependence, higher-twists, ...)?
- Impact on the \textbf{choice of a fitting strategy}?
Overview of current extraction methods.
Problems: Model dependence? Uncertainties?

Hybrid: Local / global fit

Option 1 Local fits and then smoothness assumption.


- Avoid unphysical oscillations between different \((x_B, t, Q^2)\) bins by comparing to a **global fit by a smooth function**:

\[
H^+ = 2 \sum_{n=0}^{N} \sum_{l=0}^{n+1} B_{nl}(t) \theta(|x| < \xi) \left(1 - \frac{x^2}{\xi^2}\right) C_{2n+1}^{(3/2)} \left(\frac{x}{\xi}\right) P_{2l} \left(\frac{x}{\xi}\right)
\]

- Number of fit parameters describing the \(B_{nl}\) coefficients **increases with** \(N^2\)...Extension to other GPDs seems difficult.

- **Extrapolation** problem left open.
Overview of current extraction methods.
Problems: Model dependence? Uncertainties?

**Hybrid : Local / global fit**

**Option 2** Local fits and then 1-parameter fit.


- Size of error bars reflects **systematics** of local fits.
- **Extrapolation** problem take care of by model-dependent 1-parameter parameterization.

H. Moutarde | Nonperturbative field theory 2017 | 21 / 41
Overview of current extraction methods.
Problems: Model dependence? Uncertainties?

Neural networks
Exploratory stage for GPDs.

Kumericki et al., JHEP 1107, 073 (2011)

- Already used for PDF fits.
- **Almost model-independent**: neural network description, twist-2, $H$-dominance?
- Good agreement between model fit and neural network fit in the fitting domain.
- **More reliable uncertainties** in extrapolations?
- Overtraining as a generic feature of (too) flexible models.
Summary of first extractions.
Feasibility of twist-2 analysis of existing data.

- **Dominance** of twist-2 and **validity** of a GPD analysis of DVCS data.

- \textit{Im}H **best determined**. Large uncertainties on ReH.

- However sizable **higher twist contamination** for DVCS measurements.
Software for the phenomenology of GPDs.
Different questions to be answered with the same tools.
Software for the phenomenology of GPDs. Different questions to be answered with the same tools.
PARTONS framework

PARtonic Tomography Of Nucleon Software
Nucleon tomography

Motivation
- Mass without mass
- Nucleon structure
- Content of GPDs

Scaling regime
- Experimental access
- DVCS kinematics
- Universality tests

Extractions
- Dispersion relations
- Extraction methods

PARTONS framework

Design
- Architecture
- Fits results

Conclusions

Computing chain design.
Differential studies: physical models and numerical methods.

Experimental data and phenomenology
- Full processes

Computation of amplitudes
- Small distance contributions

First principles and fundamental parameters
- Large distance contributions
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Scaling regime
- Experimental access
- DVCS kinematics
- Universality tests

Extractions
- Dispersion relations
- Extraction methods

PARTONS framework

Design
- Architecture
- Fits results

Conclusions

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Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework
Design
Architecture
Fits results

Conclusions

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First principles and fundamental parameters

GPD at $\mu \neq \mu^\text{ref}_F$

Evolution

GPD at $\mu^\text{ref}_F$
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---

**Computing chain design.**

**Differential studies: physical models and numerical methods.**

- **Experimental data and phenomenology**
  - DVCS
  - TCS
  - DVMP

- **Computation of amplitudes**
  - DVCS
  - TCS
  - DVMP

- **First principles and fundamental parameters**
  - GPD at $\mu \neq \mu_F^{\text{ref}}$
  - GPD at $\mu_F^{\text{ref}}$

- **Evolution**

- **Many observables.**
- **Kinematic reach.**

---

H. Moutarde  |  Nonperturbative field theory 2017  |  25 / 41
Computing chain design.
Differential studies: physical models and numerical methods.

Experimental data and phenomenology

Need for modularity

Computation of amplitudes

First principles and fundamental parameters

- Many observables.
- Kinematic reach.

Perturbative approximations.
- Physical models.
- Fits.
- Numerical methods.
- Accuracy and speed.

Evolution

GPD at $\mu \neq \mu_F^{\text{ref}}$

GPD at $\mu_F^{\text{ref}}$
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Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework

Design
Architecture
Fits results

Conclusions

Experimental data and phenomenology
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Evolution

GPD at $\mu_F^{\text{ref}}$
Computing chain design.
Differential studies: physical models and numerical methods.

Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework

Design
Architecture
Fits results

Conclusions

Experimental data and phenomenology
Need for modularity
Computation of amplitudes

First principles and fundamental parameters

Many observables.
Kinematic reach.

Perturbative approximations.
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Nucleon tomography

Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extractions
Dispersion relations
Extraction methods

PARTONS framework

Design
Architecture
Fits results

Conclusions

Experimental data and phenomenology

Need for modularity

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DVCS
TCS
DVMP

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Motivation
Mass without mass
Nucleon structure
Content of GPDs

Scaling regime
Experimental access
DVCS kinematics
Universality tests

Extracts
Dispersion relations
Extraction methods

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Architecture
Fits results

Conclusions
Towards the first release.
Currently: tests, benchmarking, documentation, tutorials.

- 3 stages:
  1. Design.
  2. Integration and validation.

- Flexible software architecture.


- 1 new physical development = 1 new module.

- Aggregate **knowledge** and **know-how**:
  - Models.
  - Measurements.
  - Numerical techniques.
  - Validation.

- What *can* be automated will *be* automated.
Steps of logic sequence in parent class.

Model description and related mathematical methods in daughter class.
Flexibility.
Example: implementation of new coefficient functions.

- A DVCS coefficient function module generically outputs a complex number when provided \((\xi, t, Q^2, \mu_F^2, \mu_R^2)\).

```cpp
virtual std::complex<double> compute(
  double xi, double t, double Q2, double MuF2,
  double MuR2, GPDType::Type gpdType) = 0;
```

This module can be anything:
- Constant CFFs for local fits.
- CFFs for massless quarks.
- CFFs for heavy quarks.
- CFFs with TMC.
- ...
Modularity and automation.
Parse XML file, compute and store result in database.

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- Architecture
- Fits results

**Conclusions**
Modularity and layer structure.
Modifying one layer does not affect the other layers.

**Nucleon tomography**

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- Design
- Architecture
- Fits results

**Conclusions**
Automation and nonregression.
Mnemosyne, the PARTONS project database server.

- Keep track of validated results.
- Systematic nonregression tests.
- Help preparing new releases.
- Store experimental data.
- Store grids of new models.
- Post processing?
- Time consuming fits?
Handling experimental data. Using the power of SQL for data selections.

- All fixed-target DVCS data collected at Jefferson Lab are stored in the database used for fits.
- No data about TCS or DVMP so far.
- Including **all existing DVCS data sets** in Mnemosyne is a matter of hours.
- Data selection from SQL requests for fits.

```sql
-- Kinematics --
INSERT INTO observable_kinematic (bin_id, xB, t, Q2, E, phi) VALUES(0, 0.19400, 0.11000, 1.68000, 5.93200, 25.00000);
SET @last_observable_kinematic_id = LAST_INSERT_ID();

-- Value and uncertainties --
INSERT INTO observable_result (observable_name, observable_value, stat_error_lb, stat_error_ub, syst_error_lb, syst_error_ub, total_error, observable_kinematic_id) VALUES('Alu', 0.37000, 0.23000, 0.23000, 0.01000, 0.01000, 0.00000, @last_observable_kinematic_id);
```
GPD or CFF fits (1/6).
Local fit of CFFs.

First local fit of pseudo DVCS data, Sep. 26th, 2016

The first reasonable fit with PARTONS_Fits! 12 AUL and 12 ALU asymmetries fitted together.

The true values of fit_CFF_H_Re and fit_CFF_H_Im are 0.06672466940113253 and 12.42311418138908
GPD or CFF fits (2/6).
Global fit of CFFs: border function formalism.

Succesful global fit of Jefferson Lab DVCS data (DIS 2017)

**FIT ANSATZ**

**GPDs H and \( \bar{H} \):**

\[
H^q(x, x, t, Q^2) = H^q(x, 0, t, Q^2) \times r^q(x)
\]

- composed of GPD at \((x, 0, t)\)
- and skewness function

**GPDs H:**

\[
C_H(t, Q^2) = C_{\text{sub}} \times \exp(a_{\text{sub}}t)
\]

- so far proposed ad-hoc
- weak sensitivity of data on this term

**GPDs E and \( \bar{E} \):**

\[
\mathcal{E}(\xi, t, Q^2) = N_E \times \mathcal{E}_{\text{GK}}(\xi, t, Q^2)
\]

\[
\bar{\mathcal{E}}(\xi, t, Q^2) = N_{\bar{E}} \times \bar{\mathcal{E}}_{\text{GK}}(\xi, t, Q^2)
\]

- GK CFFs
GPD or CFF fits (3/6).
Global fit of CFFs: border function formalism.

Data points and fit results

**RESULTS**

- **Kinematic cuts**
  - $Q^2 > 1.5 \text{ GeV}^2$ (where we can rely on LO approximation)
  - $-t / Q^2 < 0.25$ (where we can rely on GPD factorization)

- **$\chi^2 / \text{ndf}$**
  - $3272.6 / (3433 - 7) \approx 0.96$

- **Free parameters**
  - $a_{\text{Hsea}}, a_{\text{Hval}}, a_{\text{Hsea}}, C_{\text{sub}}, a_{\text{sub}}, N_E, N_E$

- **$\chi^2 / \text{ndf per data set}$$^\dagger$$

---

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reference</th>
<th>Observables</th>
<th>N points all</th>
<th>N points selected</th>
<th>chi2</th>
<th>chi2 / ndf</th>
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<tbody>
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<td>[1] KINX2</td>
<td>$a_{UU}$</td>
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<td>120</td>
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<td>305</td>
<td>338.1</td>
<td>1.13</td>
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</table>

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GPD or CFF fits (4/6).
The second global fit of CFFs in the valence region.

Careful statistical analysis

<table>
<thead>
<tr>
<th>Parameters and correlation matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>H a sea</td>
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<tr>
<td>H a val</td>
</tr>
<tr>
<td>H a sea</td>
</tr>
<tr>
<td>C sub</td>
</tr>
<tr>
<td>a sub</td>
</tr>
<tr>
<td>N E</td>
</tr>
<tr>
<td>N E</td>
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<tr>
<td>H a sea</td>
</tr>
<tr>
<td>C sub</td>
</tr>
<tr>
<td>a sub</td>
</tr>
<tr>
<td>N E</td>
</tr>
<tr>
<td>N E</td>
</tr>
<tr>
<td>N E</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GPD Parameter</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>H Cu val</td>
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<td>-</td>
</tr>
<tr>
<td>H Cu sea</td>
<td>1.27</td>
<td>-</td>
</tr>
<tr>
<td>H Cd val</td>
<td>1.2</td>
<td>-</td>
</tr>
<tr>
<td>H Cd sea</td>
<td>1.27</td>
<td>-</td>
</tr>
<tr>
<td>Hilde Cu val</td>
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<td>Hilde Cu sea</td>
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<td>-</td>
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<tr>
<td>Hilde Cd val</td>
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<td>Hilde Cd sea</td>
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<tr>
<td>Etilda N</td>
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<td>0.07</td>
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</tbody>
</table>
Comparison to CLAS data

CLAS: \( A_{UL} \) and \( A_{LL} \)
@ \( x_B = 0.26, t = -0.23 \text{ GeV}^2, Q^2 = 2.0 \text{ GeV}^2, E = 5.9 \text{ GeV} \)

Good description of experimental data, large systematics coming from \( \Delta q \)

H. Moutarde | Nonperturbative field theory 2017 | 37 / 41
GPD or CFF fits (6/6).
Proton tomography from experimental data.

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Conclusions
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Conclusions and prospects.
Towards a unifying framework for GPD studies.

- A lot has been achieved in the last few years!
- **Challenging constraints** expected from Jefferson Lab, COMPASS and EIC.
- **Good theoretical control** on the link between GPD models and experimental data. **High-precision** phenomenology achievable.
- Development of the PARTONS framework for **phenomenology** and **theory** purposes.
- **Fitting engine** ready for global and local fits. **Original** global CFF fits recently achieved, meeting initial aim!
- **First release** of PARTONS... *as soon as possible!*